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Effects of changes in stock productivity and mixing on sustainable fishing and economic viability

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Within the new F_{MSY} European paradigm, this paper shows how a combination of changes in fish stock mixing, non-stationarity in productivity, and constraints on unit stock concepts undermine the effective management of fisheries, especially when management reference points are not adjusted accordingly. Recent changes in stock structures, conditions and stock mixing between eastern and western Baltic cod can jeopardize the reliability of stock assessments and of the fishery economy. We modelled how different management, individual vessel decision-making, and stock growth and mixing scenarios have induced alternative individual vessel spatial effort allocation and economic performance by affecting fishing costs and by changing the relative stock abundance and size distribution. Stock mixing heavily influences profit and stock abundance for stocks that have experienced increased fishing mortality (*F*) levels. Western cod *F* has increased from a higher total allowed catches (TAC) advised in the medium-term due to the westward migration of eastern cod while eastern cod *F* has increased from reduced growth in the east. Greater pressures on western cod and decreased eastern cod growth and conditions greatly reduce the overall cod spawning stock biomass, thus changing the landing size composition and associated fishery profits. As a cumulative effect, fishing efforts are redirected towards western areas depending on management (quotas). However, total profits are less affected when traditional fishing opportunities and switching possibilities for other species and areas are maintained. Our evaluation indicates that current management mechanisms cannot correct for potential detrimental effects on cod fisheries when effort re-allocation changes landing origins. By investigating different economic starting conditions we further show that Baltic cod mis-management could have resulted in unintended unequal (skewed) impacts and serious consequences for certain fleets and fishing communities compared with others. Our management strategy evaluation is instrumental in capturing non-linear effects of different recommendations on sustainability and economic viability, and we show that fixed *F*-values management is likely not an attainable or sufficient goal in ensuring the sustainability and viability of fisheries and stocks given changing biological conditions.

Keywords: agent-based modelling, Baltic cod, bio-economic fisheries model, decision making, long-term management plans, MSY Approach, spatial effort allocation, stock production and mixing.

Introduction

The new European Common Fishery Policy (EU, 2013) implements a Maximum Sustainable Yield (MSY) as the key fisheries management objective and states that all stocks must be exploited in accordance with this principle by no later than 2015. The relevance of using an MSY approach to manage Baltic cod (BCOD) remains questionable given that BCOD belongs to two genetically and morphometrically distinct stocks (Hüssy *et al.*, 2016) being different in productivity levels. The eastern BCOD stock (subdivisions 25–32; Figure 1) has historically been fished around the fishing mortality leading to MSY (F_{MSY}) from 2008 to 2013 and quantities of this stock have substantially increased since 2007 following several decades of overexploitation. This increase was largely due to improved recruitment production levels emerging

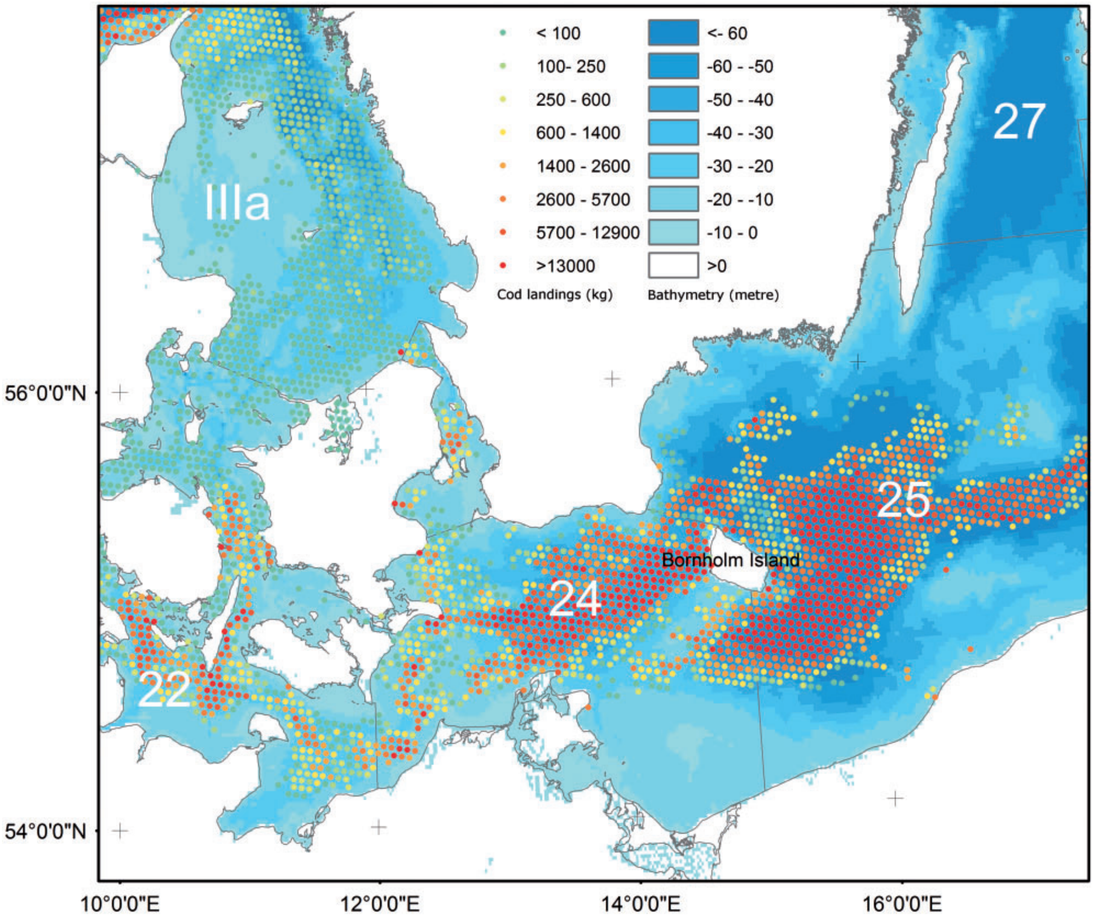

Figure 1. The Central Baltic Sea region with ICES area codings and bathymetry (in blue levels). The DISPLACE model discrete positions (underlying graph nodes; 4 by 4 km grid in IIIa, *SD* 22–25; 100 by 100 km otherwise) are shown together with the spatial origin of the 2012 cod landings in kg (coloured circles; for the selected vessels only) used to deduce area- and vessel-specific catch rates when combined with the deployed individual effort (Bastardie *et al.* 2014; see also Appendix A, catch rate).

in recent years as well as due to improved compliance with the Total Allowed Catches (TACs) principle (Eero *et al.*, 2012). Western BCOD (subdivisions 22–24; Figure 1) is by contrast estimated to be fished above F_{MSY}, though it is also managed with long-term targets in mind (ICES, 2014). Hence, it appears that MSY principles are already in place in management systems to the benefit of eastern and western cod stocks, the broader ecosystem, and fisheries. Unfortunately, since 2014, no analytical assessment of Eastern cod has been available, and a range of adverse developments (e.g. low nutritional status levels and the disappearance of larger individuals) indicate that the stock is in distress (Eero *et al.*, 2015). Somatic growth has presumably declined in recent years, and there seem to be signs of increased natural mortality levels, likely as a result of various different biological interactions (e.g. predation and ecosystem conditions) (Eero *et al.*, 2015). In addition, it has not been possible to evaluate the exploitation level relative to F_{MSY}, thus leaving the present stock status unclear (ICES, 2014). As F_{MSY} targets assume a constant biological regime of stocks (see Larkin, 1977; Holt 2006; Longhurst, 2010, for a discussion), there appears to be a conflict between current F_{MSY} implementation and changing underlying biological conditions of Eastern BCOD.

Applying the European MSY approach to BCOD fisheries is questionable given uncertain long-term reference points that are further complicated by the spatial overlap between populations and mixed stock compositions that have changed over time. This increased abundance of Eastern BCOD in the late 2000s presented a new challenge to the management of western cod, as the two populations mix within the western management area (SD 24, Eero *et al.*, 2014) and a separate TAC is associated with each management area. Recently, Hüssy *et al.* (2016) found an increased proportion of eastern cod in the western Baltic management area relative to previous levels, indicating that mixing is likely to present a growing problem in terms of stock management if not accounted for directly via management advice. This is attributed to the fact that a mismatch between the scale of fishery management units and biological population structures can create misperceptions of the productivity and sustainable yields of fish stocks (Watson *et al.* 2011; Kerr *et al.*, 2014; Hintzen *et al.*, 2015; Clausen *et al.*, 2016).

The BCOD fisheries are of importance to numerous fishing communities, including Danish fishermen, for whom the value of landings at first trade amounted to 15 million euros in 2012 for larger Danish vessels. In response to the poor conditions of eastern cod and to changes in stock mixing, fishermen may redirect their fishing efforts toward other more rewarding areas and stocks. The stocks are structured in space and time where different fish size groups are caught in different areas at different times by fishermen with varying levels of gear selectivity and catching power, varying social motives, and varying economic priorities. All of these factors affect a fisherman's decisions when selecting fishing grounds and other operating details (Bastardie *et al.*, 2013). Precisely because of these conjugated effects, the relationship between fishing mortality and fishing effort deployed by a fishery to catch quotas on cod or other fish stocks is expected to be strongly non-linear (Harley *et al.* 2001; Mahevas *et al.*, 2011; Marchal *et al.*, 2013; Glaser *et al.*, 2014). Accordingly, this constitutes a case where changes in fish stock mixing and productivity can undermine ways in which the MSY approach is applied, long-term fishery management plans, and fishery economic efficiency levels. Assumptions regarding well-separated stock identities between eastern and western cod would further worsen our biased perceptions of stock conditions in cases where two area-based assessments (as done by ICES, 2014) do not match respective stock distributions.

We study the effects of recent changes in stock dynamics on MSY efficiency while ensuring stock sustainability and fishery economic viability, and we examine whether such changes can explain the recent dramatic decrease in the relative abundance of larger cod levels and the potential failure of management procedures. Our impact assessment on stocks and fisheries based on a scenario is tested using the Management Strategy Evaluation (MSE) framework to evaluate the degree to which biological and fleet operating model assumptions are robust to change (e.g. Kell *et al.*, 2007; Punt *et al.*, 2014; Thorpe *et al.*, 2015; Carruthers *et al.*, 2016). Our MSE specifically accounts for the presence of non-linear inter-vessel differences and for compensation opportunities in fishers' responses to regulations and changed resource conditions by applying the DISPLACE model (Bastardie *et al.*, 2014, 2015), which provides a test platform for running Monte-Carlo simulations that project scenarios of alternative harvest patterns and fishing effort distributions. We evaluate how advice and management systems are affected when a fixed *F*-value approach is followed to changing conditions of stock mixing and stock migration that produces area specific mismatches, a situation that is likely to be enhanced by very different stock conditioning patterns between eastern and western cod stocks. Potentially inappropriate advice and management strategies resulting from such situation are likely to have a significant effect on the economic viability of the catch sector and of individual fishing vessels involved in respective cod fisheries.

Material and methods

Conditioning DISPLACE based on current BCOD stock fisheries

DISPLACE accounts for parameters that determine fishermen's decisions, and it offers projections of fishing effort displacements based on expected revenues and operating costs (fuel costs) and in response to assumed spatial planning measures (Bastardie *et al.*, 2013, 2014). Simulations are based on the creation of fishing activity scenarios over a certain period of time (typically a 5-year horizon based on hourly time intervals). The operation of fishing activities in simulations is based on the actions of individual vessels in response to changes in space and time in terms of fish stock abundances and available fishing space. DISPLACE uses five different decision trees (ChooseGround, GoFishing, StartFishing, StopFishing, ChooseHarbour; see Supplementary Materials S1 and S2) to address the period during which a skipper makes decisions and operates trips at sea (Bastardie *et al.*, 2013). The tool enables users to determine the effects of spatially heterogeneous individual vessel decisions on overall system dynamics by modifying different reaction patterns (the decision trees) while also considering how flexible vessels are to exploring new areas. To use this tool, one first reproduces existing fixed observed patterns (the baseline) obtained by conditioning individual vessel monitoring system (VMS) model data coupled to logbook data, and then one can test various scenarios where each vessel can adopt more opportunistic behaviours. The movements of all Danish vessels that are larger than 12 m in length and that were active in 2012 are simulated at hourly time intervals on a $4 \times 4\,\text{km}^2$ geodesic spatial grid over Kattegat, Skagerrak in the western Baltic and over ICES *SD*25–26 in the Eastern Baltic (Figure 1) by computing shortest paths (in a semi-continuous grid) between departure and arrival locations (harbours or fishing grounds). The model only considers the set of VMS-equipped fishing vessels (vessels > 12 m), as full individual tracks at sea over the year can be reconstituted from VMS data and then further coupled to corresponding logbooks. Local stock depletion from other vessels or nations (i.e. from "other" landings) is also accounted for in the model but is not attached to particular vessels (Bastardie *et al.*, 2014). The other landings has been deduced from the more comprehensive EU STECF data (annual landings per rectangle; http://stecf.jrc.ec.europa.eu/web/stecf/ewg1313) based on a national data sampling of commercial fisheries under the EU Data Collection Framework (DCF; http://datacollection.jrc.ec.europa.eu/dcf-legislation). The "other" landings are distributed on nodes that define the stock distribution area, and their spatial abundance structure per stock by ICES rectangle is preserved.

A total of 50 stochastic runs are conducted per scenario to model the movement and discrete time catch operations of the entire Danish fleet (394 vessels were larger than 12 m in length in 2012). Among all the simulated vessels we selected 84 BCOD fishery vessels in total (with all vessels having at least 50% of their landings on BCOD in 2012), with 28 vessels fishing exclusively in the western Baltic, 6 vessels fishing exclusively in the Eastern Baltic and 50 vessels fishing in both areas. Most of the vessels are trawlers participating in two to four activities (up to nine for a few of them) each year. An otter bottom trawl (OTB) with a cod-end mesh size of 105–120 mm is the main gear used in BCOD fisheries (Figure 2). Some vessels are polyvalent enough to fish for pelagic species as well (*Sprattus sprattus* sprat, *Clupea harengus* herring, and *Ammodytes spp.* sandeel) in the BCOD North Seas. The Danish vessel landings examined represent 24% of the international TAC for western cod and 13% of the TAC for the Eastern cod. Landings made by other (smaller or foreign) vessels were not explicitly simulated. Consequently, we note that the present study focuses on how changes in stock dynamics affect the fishery economy and not vice versa.

The model methodology employed for the DISPLACE dynamic evaluation and for the coupling of spatial vessel activities to underlying resource dynamics is fully detailed in Bastardie *et al.* (2014). For each quarter year, resources (38 stocks among North and Baltic Sea fish, shellfish, and crustacean stocks) are locally (re-)distributed in space (per quarter) using information for

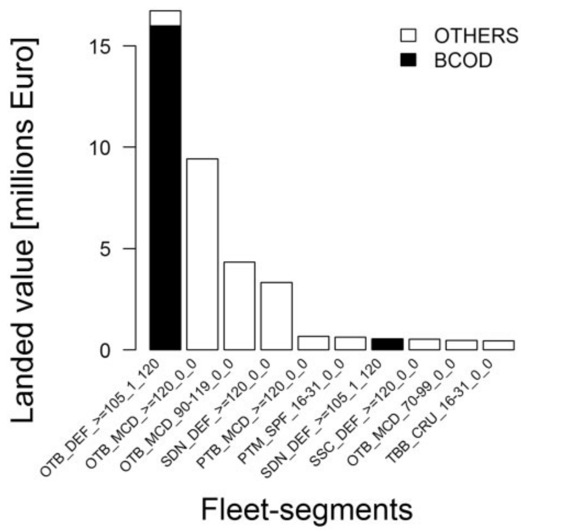

Figure 2. Declared landed value per stock (top 15) per EU DCF, https://datacollection.jrc.ec.europa.eu/) activity/métier (top 10) for vessels participating in BCOD fisheries in 2012. Stock landings have been merged except for BCOD, which corresponds to eastern and western BCOD stocks. Source: Danish logbooks coupled to harbour sales slips.

half of the year based research surveys (International Bottom Trawl Survey, IBTS, and Baltic International Trawl Survey, BITS; www.ices.dk, DATRAS) assuming the same spatial distribution between the first and last two quarters. Hence, the spatial information drawn from scientific surveys is only used to deduce the underlying stock distribution and density. In the model, each vessel depletes stocks (at hourly intervals) by taking catches as specified by a catch equation (see also Appendix A). In addition, natural fish mortalities are included. Potential effects of predator-prey interactions on other stocks (especially sprat and herring in the western Baltic) were tested, and they do not show any effects on the baseline of our simulations and they are thus not presented here. Hence, the natural mortality level varies by size group according to Andersen *et al.* (2009), but it is assumed to be constant throughout the simulation and independent of sprat and herring abundances.

The model is conditioned on the 2012 cod stock status, when eastern and western stock mixing was not taken into account in stock assessments while the proportion of eastern cod in western management areas increased substantially compared with levels recorded in the early 2000s (Hüssy *et al.*, 2016). The analytical assessment (ICES, 2014) presents the state of BCOD stocks by estimating their numbers N by age using a standard assessment methodology for these stocks. These numbers are then converted into numbers by size group following the methodology described in Bastardie *et al.* (2014), thus generating Age-Length Keys (ALKs) from a simulation of 10 000 cases of individual growth. Hence, the number by size group at the beginning of the simulation (binned into 5 cm classes) can vary depending on the Von Bertalanffy parameter curve used to estimate growth levels. The model assumes a Ricker (Ricker, 1954) spawning stock-recruitment relationship for both stocks while the effects of natural recruit variability (e.g. from external physical factors such as the reproductive volume in the Baltic Sea, etc.) are addressed by assuming a lognormal stochastic error (scenario CV = 0.2). At the start of each year, recruitment per age is deduced from the assessed spawning stock at y−1, and it is further distributed over N by size group using the ALKs.

The potential effects of fish migration from the eastern area to the western area are studied by assuming that a proportion of the overall stock N is lost from the Eastern cod stock (per size group; see Table 1) and is added to the western cod stock for the entire area at the beginning of each simulated year. The proportion of Eastern cod entering the western Baltic has been documented by Hüssy *et al.* (2016) via genetic and otolith shape analyses. Based on this information, annual migration fluxes per size group are assumed and are then applied to the overall Eastern cod population relative to the overall western cod population. Migration fluxes from east to west were obtained by analysing the 2011 proportion of Eastern cod migrants (recognized by their otoliths and genetic variations) at length in the western Baltic among the total population of western cod estimated via ICES age-based analytical stock assessment (Hüssy *et al.*, 2016). By scaling up the numbers to the entire Eastern BCOD stock (given the estimated number of individuals present in the area by ICES analytical assessments), we obtained fluxes per age from east to west. Proportions by age were then converted into proportions by size group given by the DISPLACE ALK described earlier. These biological scenarios on east-west migration assume no backwards migration and constant fluxes. Furthermore, it was not assumed that an eastern cod migrating west instantly becomes a western cod in terms of resulting differences in weight at length. Eastern cod migrants are also not subtracted from western cod numbers by age before applying the harvest control rule, therefore not basing the western cod management procedure on the true western cod abundance only. To account for a change in the biological conditions of western cod induced by (smaller) Eastern immigrants entering the model and then changing the weight and length of the average fish caught in the *SD* 24, the weight and length in the *SD* 24 area is deemed a weighted average of the eastern and western weight by size group based on the relative proportions of eastern and western cod present in the *SD* 24 area.

Model calibration

The model is calibrated to use simulated fishing mortalities *F* by age and total landings per BCOD stock by matching ICES assessment values (during the 2012 calibration year). The calibration is first performed by simulating the system one year ahead and by each time searching for multipliers to be applied to (i) the weight by size group for each cod stock and (ii) to the total amount of "other landings". Concerning (i), for average *F* outcomes to match the ICES assessed ones, we assumed that the uncertainty of animal body weight is largely responsible for the goodness of fit in *F*, while a higher individual mean weight implies a lower number of fish caught and thus a lower fishing mortality level. (ii) Landings made by non-simulated vessels (non-VMS equipped or foreign vessels) must also be parameterized to account for gaps in landing and discard data. Hence, by applying calibration multipliers 0.9 and 1.0 to the weight and size group, the best fit in 2012 for the average *F* for western cod is 0.677 based on an interval of 0.499–0.976 assessed in ICES (2014), and the simulated Spawning Stock Biomass (SSB) is recorded as 30 279 but is assessed at 41 028 tons in ICES (2014). The best fit for the Eastern cod average F is 0.322 based on an interval of 0.266–0.521 assessed in ICES

Table 1. Stock and management attributes of area-based eastern and western Baltic cod stocks compiled from different sources.

		Western cod (COD.2224)	Eastern Cod (COD.2532)	References
Biological attributes	Numbers by age in thousands (ages 0–12)	{119611, 33827, 31761, 19833, 15854, 4046, 952, 264, 0, 0, 0, 0, 0}	{0, 0, 208564, 144640, 77034, 38561, 22359, 10361, 6286, 0, 0, 0, 0}	ICES (2013)
	Von Bertalanffy Linf	100.0	89.3	ICES (2015)
	Von Bertalanffy k	0.180	0.187	ICES (2015)
	Condition parameter a	0.00700	0.00600	www.fishbase.org
	Condition parameter b	3.1600	3.1503	www.fishbase.org
	Maturity L50 (cm)	30	28	ICES (2015)
	Natural mortality M per size			Andersen *et al.* (2009)
	Consumption rate h ($g^{1/3}.y^{-1}$)	27	27	
	Size selection parameter φ	0.12	0.12	
	Migration (fraction east to west per bin of 5 cm body length)	None	{0.0604, 0.0048, 0.0190, 0.0261, 0.0156, 0.0129, 0.0143 0.0139, 0.0135, 0.0108, 0.0103, 0.0097, 0.0092, 0.0368, 0.2000}	Hüssy *et al.* (2016)
	SSB-R Ricker a	3.11	0.2	Goodwin *et al.* (2006)
	SSB-R Ricker b	1.32e-05	2.00e-07	Goodwin *et al.* (2006)
Management attributes	Minimum landing size (cm)	38	38	EU
	TAC in tons (2012)	17 072	50 972	ICES (2014)
	LTMP			EC (2007)
	Fbar min, max ages	3–6	4–6	
	% *F* decrease a year	10	10	
	% TAC constraint	15	15	
	FMSY-approach			ICES (2013)
	F-value	0.26	0.46	
	B MSY-Trigger (tons)	36 400	88 200	

(2014), and the SSB is 192 802 tons but with 153 584 tons assessed in ICES (2014). Finally we found calibration multipliers 2.1 and 1.5 on other landings (landings made by the non-simulated vessels due to non-VMS-equipped vessels or vessels belonging to other nations) to obtain simulated total landings that are equivalent to the observed TACs for eastern and western cod, respectively (see Supplementary Materials S3).

Management procedure and *F*-value targets

BCOD is split into two stocks with distinct management areas (west *SDs* 22–24; east *SDs* 25–32), but the same management procedure has historically been applied to each stock as specified in long-term management plans (LTMPs) for cod stocks described by the EU Commission (2007), with long-term *F* targets at 0.6 and 0.3 established for western and Eastern cod, respectively. These LTMPs stipulate that *F*s should decrease by 10% each year until reaching *F* targets. In 2013, the EU decided to apply the F_{MSY} approach to all European marine fish stocks with the goal of reaching F_{MSY} by 2015 (EC, 2013). In our analyses, we assume that these pre-existing BCOD LTMP targets correspond to exploitation rates that ensure MSYs (EC, 2012). The simulated LTMP is embedded in a MSE framework that includes a number of key actions: forecast the population N at $y+1$ from N at $y-1$ assuming perfect knowledge of N given by the simulations; apply a decrease in *F* by 10% twice (for y and $y+1$) following the plan; set the TACs from the forecasted *N* and the observed weight by age and accordingly from removals corresponding to the LTMP *F*- targets; determine whether the TAC falls within the $\pm$15% interval (by default) relative to the TAC for year y. The start year (2012) used for this simulation is the last year for which an analytical assessment of Eastern BCOD is available. In addition, during this year, western BCOD assessments were still area-based, i.e. not taking into account stock mixing. The forward projection from 2012 allows for discussions on likely drivers of present (2015) uncertain stock conditions (ICES, 2015).

Fisheries and management scenarios

A set of baseline simulations was performed to calibrate the model and to evaluate whether it was able to mimic the observed data. Thereafter, we modelled and investigated the final baseline and a series of scenarios (Table 2) on alternative biological conditioning (the growth and importance of stock mixing), vessel decision-making options (fuel saving, responses to fish prices, and knowledge sharing) and management regimes (LTMP or F_{MSY}). Performance indicators of stock and fleet dynamics were drawn for each scenario and were compared in relative terms at the overall and individual scales based on stock conditions (SSB, *F*), trip patterns (steaming vs. fishing effort; trip duration), fleet catches (landings and discards), fleet economy [Gross Value Added (GVA); euros], and energy efficiency [value per unit fuel (VPUF); euro per litre fuel] while also determining the spatial distribution of fishing effort and relative change. For each scenario, each vessel owns a specific individual landings quota on each stock. This individual quota is a share of the total Danish quota on these stocks (given by individual historic landings) after subtracting the total for non-simulated vessels (e.g. vessels < 12 m). The total Danish share is a share of all European TACs following the relative stability principle for EU member states. The respective TACs for Eastern and western cod stocks fluctuate

Table 2. Description of the biological, fleet displacement and management scenarios used alone or in combination with the present evaluation.

Scenario type	Scenario name	Description
Biological scenarios	+Linf09, +Linf08, or +Linf07	The Von Bertalanffy growth asymptotic size, Linf, parameter is downscaled 0.9, 0.8, or 0.7 times relative to the baseline value for Eastern cod (individual cod in the east) (Table 1) leading to a reduced average length for the size group for the entire simulation horizon.
	+M1.1	The natural mortality M parameter is increased by 1.1 relative to the baseline for Eastern cod size-based M leading to an increase in mortality for the size group in the simulation.
	+Mig, +2Mig or +2then0Mig	The fraction of Eastern cod migrating west applies per size group (+Mig), and it may have increased 2-fold or it may have stopped in year 4. Migration scenarios had some effects on the assessment. Hence, the "true" age for the Western cod stock (cod caught in the Western Baltic Sea) was deduced by removing the proportion of cod that was Eastern cod, and the "true" fishing mortalities by age were further deduced. In contrast, the management procedure does not distinguish between Western and Eastern cod in the catches, in the SSB for recruits and in the perceived Fs when setting TACs along the LTMP.
	+Slim0.97	The weight W parameter is reduced by 0.97 relative to the baseline for the Eastern cod average body weight per size group, thus reducing the stock condition.
	+BiolSces	This combines all biological scenarios (i.e. +Linf09+Slim0.97+M1.1+Mig) affecting biological traits of the Eastern cod stock.
Fleet displacement scenarios	Baseline	The baseline forces each vessel to select locations with the highest expected profit for the current departure port, the expected cost for fishing, and experienced catch rates [details shown in Bastardie *et al.* (2014)]. For the fishing grounds they know best, effort allocation will change when seasonal changes occur for the most profitable grounds. This scenario is used as a baseline to compare with the following scenarios.
	+SaveFuel	As a result of an assumed 20% increase in fuel price, vessels restrict their visits to certain fishing grounds (the three first most heavily frequented vessel-specific fishing grounds) to cut their expected fuel consumption (e.g. Poos *et al.*, 2013) and costs by 20%, regardless of the expected catch rate is at these locations. This scenario is incompatible with the optimization of high-profit grounds, which is thus disabled.
	+priceTargets	From current daily fish prices among fish stocks that it targets (at best five stocks), the vessel fishes or not based on probabilities that fall below or exceed a threshold for the highest stock price among all targets. Daily fish prices are given by pre-existing time series generated at the start of the simulations.
	+sharedKnowl	On each harbour, the visited fishing grounds list is shared among vessels displaying the same activities (a metier), meaning that each skipper goes beyond what they already know to explore potentially new fishing grounds relevant to more frequent activities.
Management scenarios	+FMSY	The current LMTP (EC, 2007) is replaced by the true F_{MSY} approach including a Btrigger to target with a lower *F*-value (the *F* target is multiplied by the ratio of FMSY to the perceived F) when the SSB is perceived to be less than Btrigger. In 2012, ICES (ICES, 2013) decided to advise on TACs based on this approach, and the FMSY for EB cod was recorded at 0.46 and the BMSY trigger was recorded at 88,200 t. For WB cod (area based assessment for *SD* 22–24, including eastern cod in the area), the FMSY was 0.26, and the Bmsy trigger was 36 400 t. Btriggers are SSBs.

proportionally (as defined in Bastardie *et al.*, 2014) to the overall annual TACs issued from the two cod LTMPs. The Danish quotas (as well as the total international TAC) for cod stocks have not been fully utilized in recent years (e.g. 86.8 and 72.5% for western and Eastern cod in 2012, respectively), as vessels have been unable or unwilling to catch their quotas, thus resulting in effort reallocation in certain areas. The TACs for other stocks are assumed to be constant.

Results

Effects on stocks performance

For the scale of model conditioning changes tested, certain growth and mixing regimes are highly influential and detrimental in terms of ensuring the sustainability of Eastern stocks. Risks of stock collapse emerge when cod asymptotic size is decreased by 20% (Figure 3; +Linf0.8). A conditioning level falling below the baseline will affect stock conditions as more individuals are required to fulfil the TACs and to reach a certain SSB level, thus resulting in insufficient numbers of Eastern cod to sustain the population in the long term. The cumulative effects of a lower growth regime added to lower conditioning (+biolSces) led the Eastern stock to a collapse trajectory (Figure 3). As some Eastern cod migrate west, landings of western cod stock also declined in weight as a consequence when Eastern cod is in poor condition (Figure 3; +Linf07). This has been the case despite the fact that vessels have redirected their efforts towards fishing for western cod (as described below for +biolSces).

Eastern cod growth and mixing changes lowered long-term revenues from cod fisheries by 70% (Figure 3; +Mig) but only moderately affected overall fishery profitability levels. This has occurred because the profitability of the selected vessels is derived from fisheries for other stocks and in other areas (Figure 4, e.g. sprat and herring in the Baltic and North Sea). For instance, the

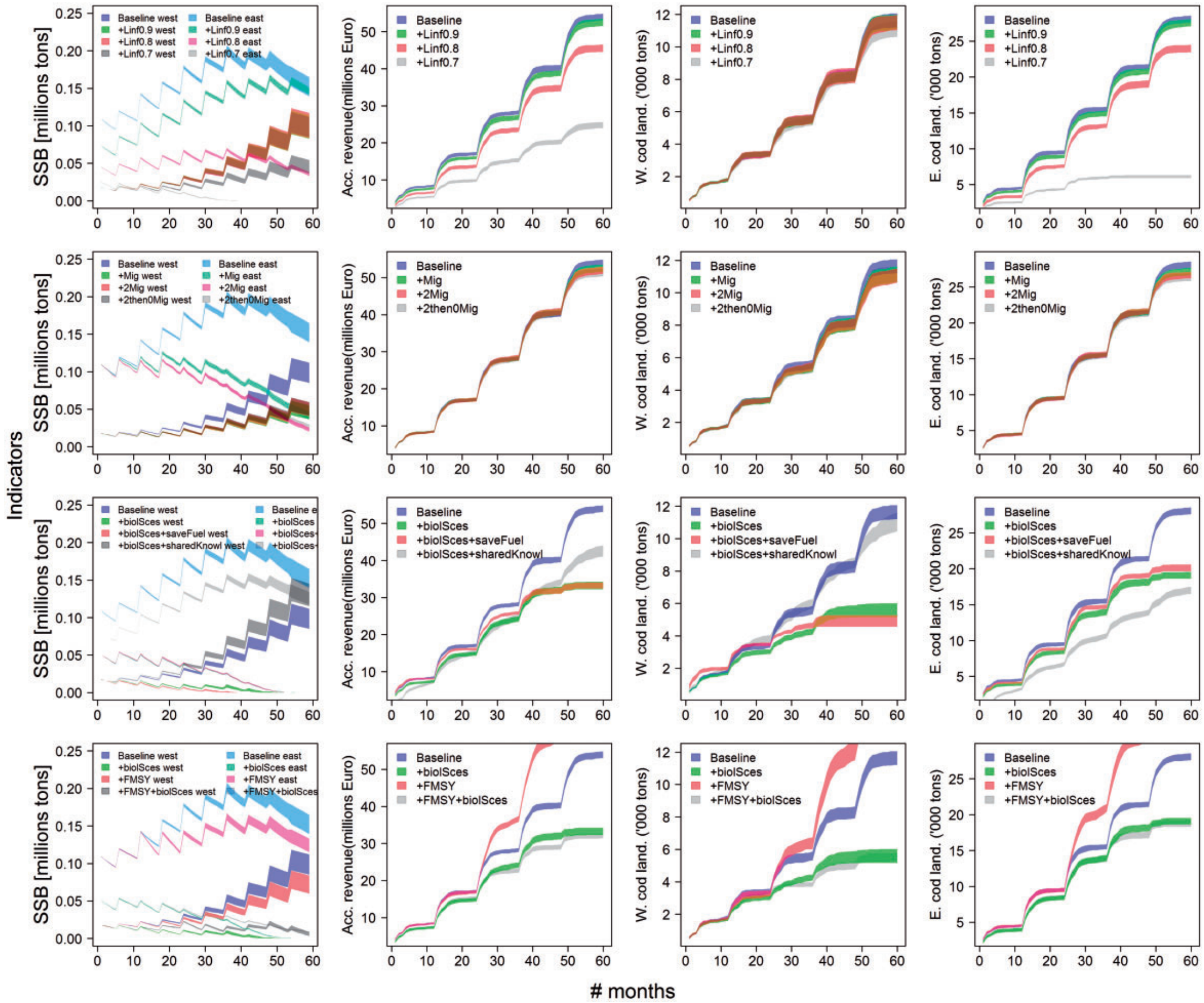

Figure 3. Cod SSB, accumulated revenue, and cod landings for Western and Eastern cod over the simulation period up to the horizon time (2015) when focusing on Danish BCOD fisheries (50 stochastic replicates per scenario). This is developed according to a simulated range of values for the Von Bertalanffy parameter Linf; according to migration fluxes from east to west; according to selected scenarios concerning decision making processes; or according to different management regimes, i.e. LTMP and F_{MSY}. Note that SSB for Eastern cod is recorded as 0 for Linf values, which equals a factor of 0.8 and 0.7 of the baseline.

western cod stock also contributes to the final overall profit. The accumulated baseline landed value is ca. 50 for BCOD out of 200 million euros in total (i.e. revenue from cod and other stocks) after five years. In addition, along with declining Eastern cod stocks, cod landings could be maintained from smaller individuals unless capturing smaller cod involves too much effort. Hence, vessel physical time limits at sea (365 days) are sometimes reached given declining Catch Per Unit Efforts (CPUEs) and collapse trajectories. In the latter case, BCOD fisheries are only worth ca. 20 million euros vs. baseline levels, with more than 50 million euros accumulated after 5 years. It is remarkable that the target level of $F = 0.3$ for the long-term Eastern cod management plan is not attainable within all of the tested scenarios affecting growth and stock mixing (Figure 5; +biolSces), as the SSBs consist mainly of smaller and less mature individuals, thus lowering recruitment levels. Accordingly, the management procedure applied in the simulations cannot cope with such a dramatic decline due to TAC constraints ($\pm 15\%$ from a TAC in y to the TAC in $y + 1$).

Under the enhanced migration scenario, Eastern cod stock levels declined due to losses to the western stock (Figure 3). When enhanced migration results in a higher fishing mortality level for Eastern cod (Figure 5), a much higher fishing mortality level for western BCOD results relative to the baseline. We expect higher migration levels to provoke a trade-off between fewer true western cod collected in catches (because catches include both Eastern and western cod) and risks from decoupled and higher-than-necessary TACs advised for western cod based on biased management procedures. According to our analyses, management procedures predicted the F for western cod to be lower than the true value in addition to overestimating recruits from the overestimated SSB when Eastern cod were also counted in the SSB for

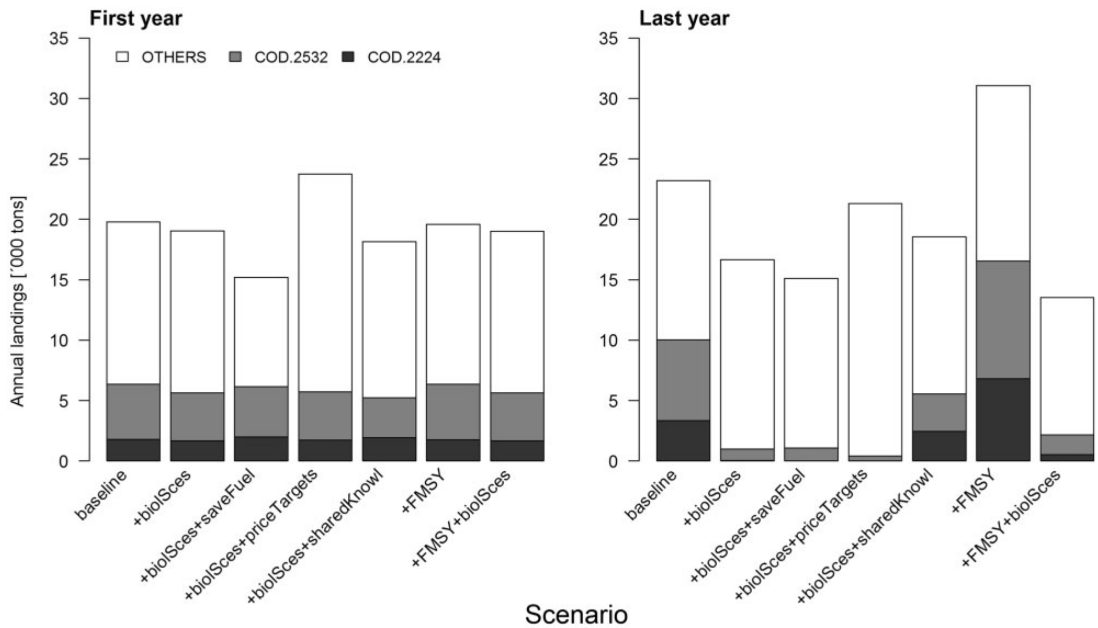

Figure 4. First and last year landing composition of the simulation period per scenario (average over the 50 runs—top 15 stocks merged except for ICES *SD* 22–24 western cod and *SD* 25–32 eastern cod). Here only the Danish vessel involved in BCOD fisheries was selected. Dynamics of BCOD stocks are explicitly simulated, but this does not prevent vessels in the model from fishing for other stocks depending on their specific CPUEs (see the text for a detailed explanation).

western cod. Accordingly, the western stock is at risk of encountering high *F*s and TACs even if sustained by cod migrants from the east. This effect is enhanced when eastern cod are less plentiful than western cod.

Effects on fishery effort allocation and economy

Fisheries do not compensate for losses in BCOD fisheries by redirecting their efforts toward other stocks (given assumed constant individual vessel quotas on those stocks) (Figures 4 and 6). Profits (NPV; net present value) of GVA with a 4% discount rate recommended by the EC http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm) fall below the baseline with a declining trend when growth is decreased and when stock mixing occurs (by 5%). In turn, the catch rate of Eastern cod declines significantly (Figure 6; +biolSces). East-west migration patterns had a minor effect on overall revenues (Figure 4; +Mig), but these trends had major effects in conjunction with the lower growth regime (Figure 6; +biolSces).

The scenario simulations adapt trip patterns in an attempt to save 20% of fuel costs (+saveFuel) or by exploring new grounds. The latter approach involves changing fishermen-preferred fishing grounds to shared grounds (+sharedKnowl), which again is based on shared knowledge at departure harbours among vessels that highly influence overall effort allocation patterns among stocks (Figure 4) and fishing areas (Figure 7). However, both scenarios led to losses in profitability. Vessels attempting to save fuel did spend more time fishing than steaming and focused on closer but less fruitful fishing grounds, thus decreasing their profits by more than 30% (Figure 6). This also increased pressures on western cod stock (Figure 5). Vessels that fished when fish prices were perceived to be suitable (+priceTargets) performed better even when costs for fishing were higher due to the existence of more steaming efforts at sea. This was especially the case when fishermen attempted to reach western cod fishing areas (50% more effort; Figure 6). Changes in trip patterns and fishing grounds visited serve as a suboptimal solution for the involved vessels, as these strategies in most cases adapted landing species compositions to larger quantities of western cod (Figure 4) to the detriment of Eastern cod catches. This also entailed traveling longer distances to reach fishing grounds.

Slower growth combined with stock mixing induced changes in spatial effort allocation as quantified from the simulation outcomes (Figure 7; +biolSces). Effort allocation is dependent on experienced profitability and CPUE downscaling for biological scenarios. Hence, lower growth and increased migration resulted in effort reallocation westward (Figure 7 and Table 3; +3% in *SD* 24), further east (Table 3; +2% in *SD* 28), or toward the North Sea. These shifts increased fishing costs as well as average travel distances. Vessels fishing for Eastern cod reallocated efforts to remote eastern grounds because changes in size compositions induce CPUE declines in traditional fishing areas due to relatively larger quantities of small fish found in these areas (Supplementary Materials S4). In addition, westward movements were constrained by area-based TACs. Alternative fishery decision-making resulting dramatic changes (Figure 7) in the magnitude and/or distribution of efforts (but not outside the limits of known space given the present simulation settings). When vessels respond to fish prices (+priceTargets), spatial effort allocation patterns may remain the same but pressures on cod stocks grow more intense due to greater efforts made overall. This occurs when a vessel begins fishing as soon as the price is found to be suitable (among five target stocks) without other constraints. The sharing of knowledge on valuable areas in harbours (+shareKnowl) led to a concentration of fishing efforts in a few western Baltic fishing areas among BCOD vessels searching for the most profitable areas in ICES *SD* 22 and 24 and in remote areas far east towards *SD* 27 (Table 2). Accordingly, the average trip distance travelled increased in these scenarios. Alternatively,

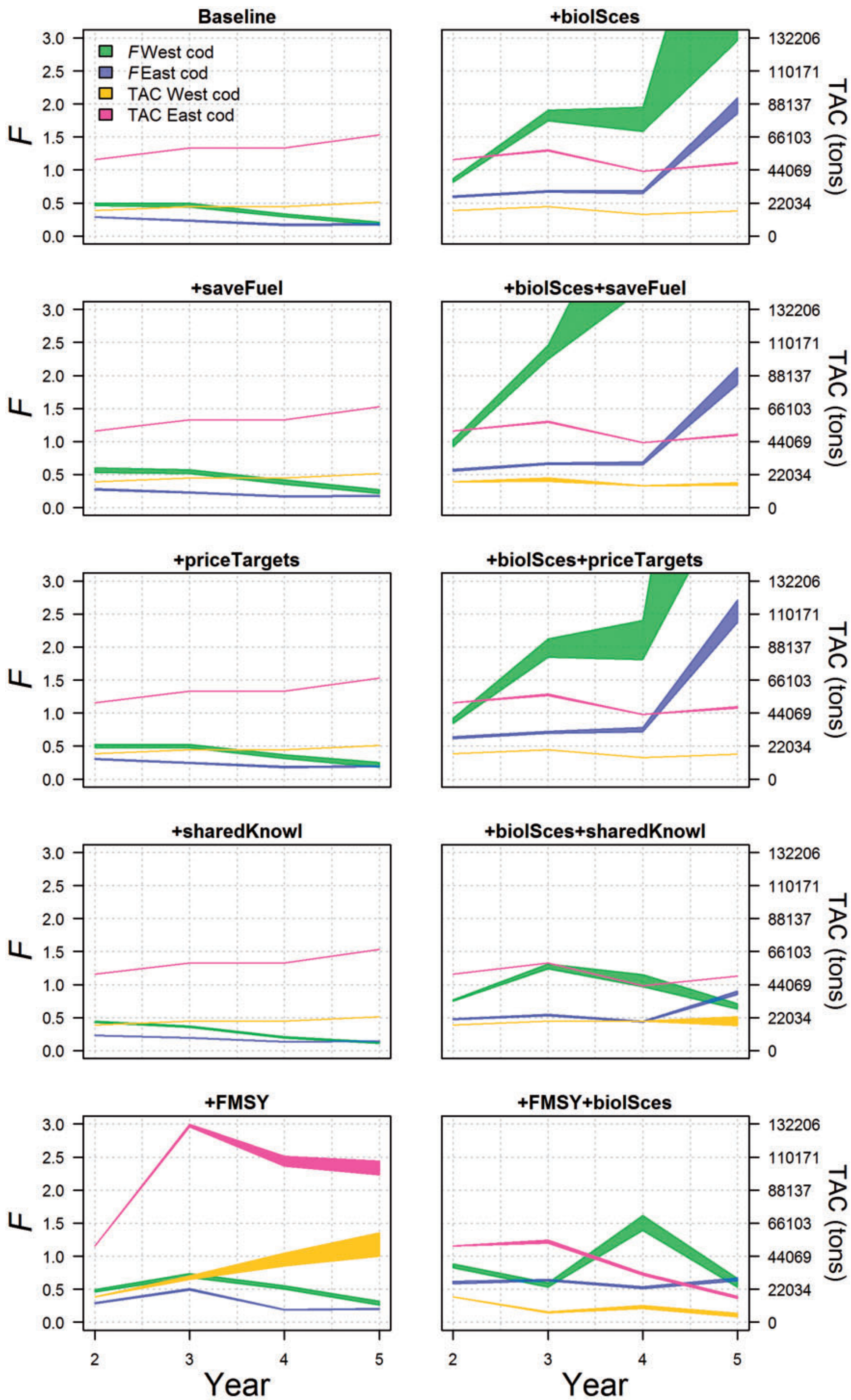

Figure 5. Simulated average annual fishing mortalities per stock (Fbar) for each scenario and over the four forecasted years, and TAC (in tons) implemented according to the long-term cod management plan procedure or the FMSY approach applied within the simulation for each scenario and over the 4 forecasted years. The 95% percentile is given from the 50 runs per scenario.

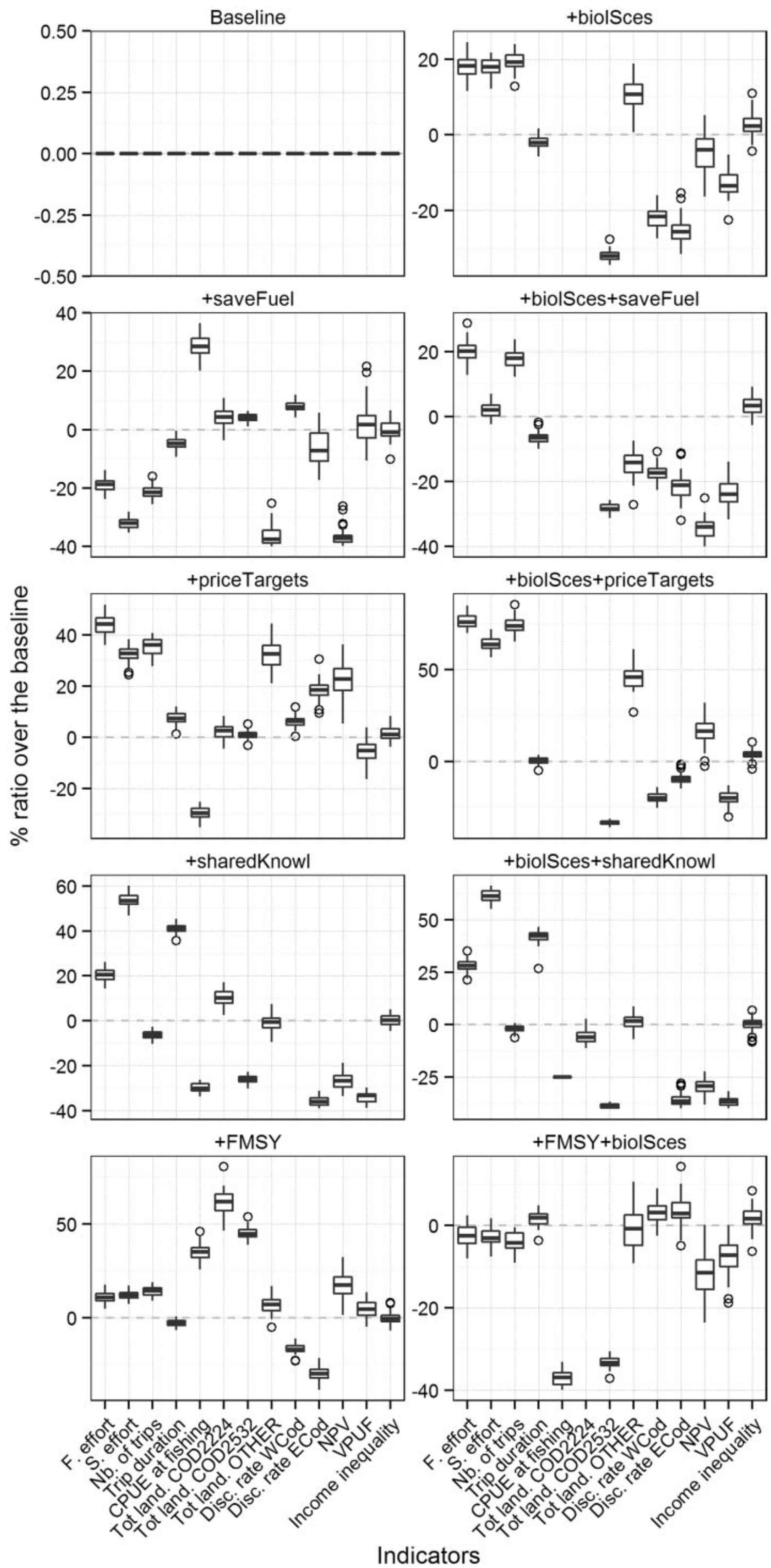

Figure 6. Comparison of aggregated scenario outcomes (50 stochastic replicates per scenario) on vessel performance indicators (percent relative to the baseline) for vessels involved in BCOD fisheries. The percentages are relative to the baseline situation for Fishing efforts; Steaming efforts; The number of trips; Trip durations; CPUE for catching BCOD; Total landings for western, eastern and other stocks; Discard rates of Western and Eastern cod; NPV with a 4% annual discount rate; VPUF; and income inequality computed based on the Hoover Index. The baseline is given by the 'focus on high-profit grounds' scenario, including the ChooseGround and stopFishing decision trees shown in Supplementary Materials.

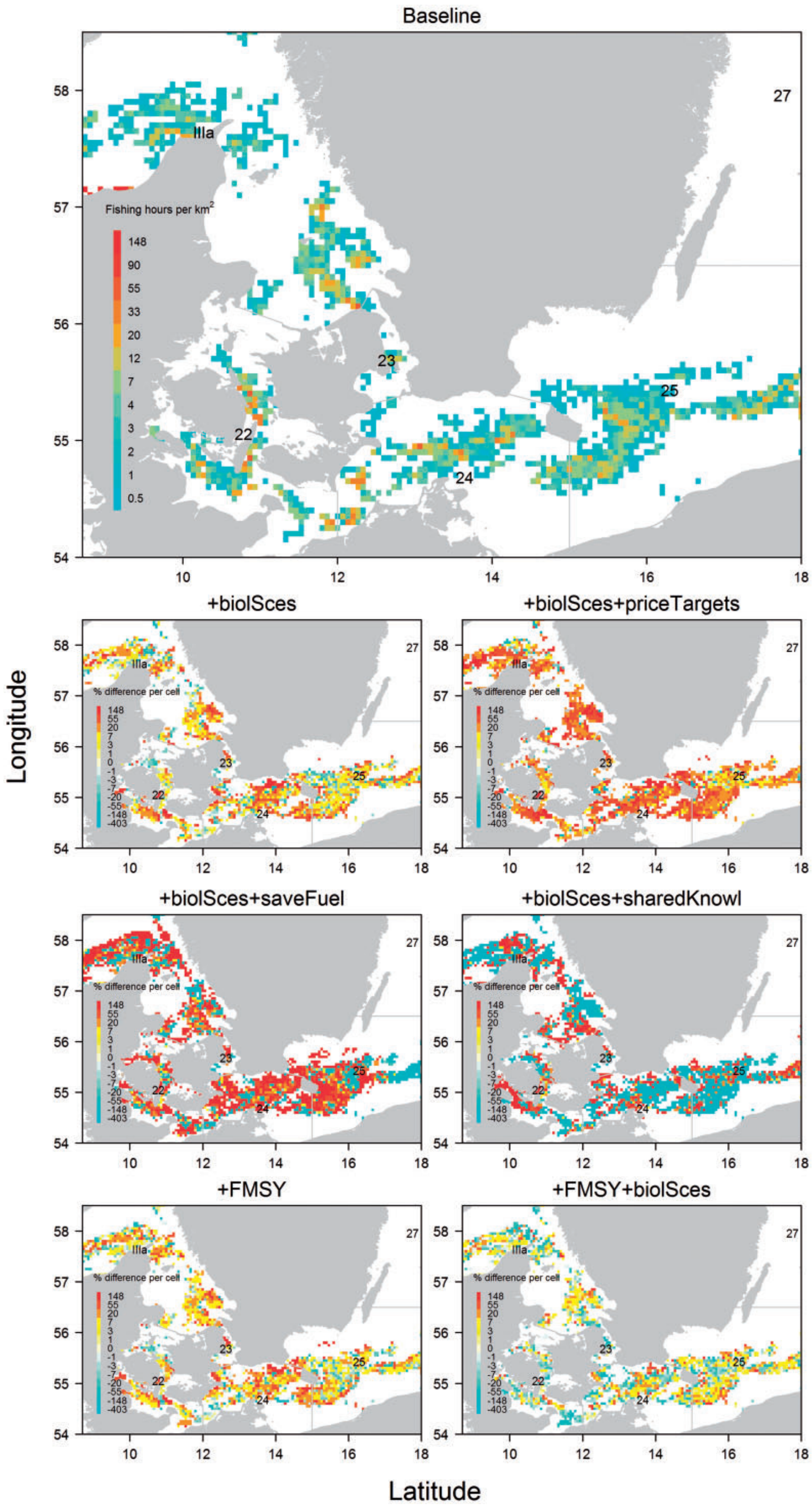

Figure 7. Baseline spatial distribution of Danish fishing efforts and the percentage of relative change (per grid cell of 50 km^2) per scenario. Fishing efforts are given as the accumulated fishing hours over the 5-year simulation horizon averaged over the 50 replicates per scenario. No efforts are displayed in *SD* 27 (or in other areas that are not shown) because the effort allocation level is not simulated at the same geographical scale in this area.

Table 3. Accumulated fishing hours (for all simulated Danish vessels) per ICES area for the baseline conditions and percentage changes relative to the baseline for other scenarios

Scenario	22	23	24	25	26	Other	Total
Baseline (Fishing hours)	78 786	5219	93 831	104 007	529	502 302	784 676
+Linf0.9	−0.7	2.7	−0.8	1.4	3.0	0.4	0.3
+Linf0.7	4.4	7.9	13.1	16.0	32.0	5.0	7.4
+Linf0.8	−0.1	1.3	0.3	1.2	−0.5	0.3	0.4
+Mig	3.2	4.9	5.3	2.8	5.7	2.5	2.9
+2Mig	3.8	4.4	5.6	2.7	5.5	2.2	2.8
+2then0Mig	3.8	4.4	5.6	2.7	5.5	2.2	2.8
+biolSces	10.1	10.2	15.9	9.8	26.5	5.2	7.6
+priceTargets	23.0	23.2	21.3	29.7	25.3	40.4	34.8
+biolSces+priceTargets	40.1	37.7	50.2	43.1	54.3	49.3	47.6
+saveFuel	−11.9	14.8	−3.2	1.1	−96.3	−14.1	−10.4
+biolSces+saveFuel	10.5	42.0	31.6	26.8	−92.5	−0.2	8.5
+sharedKnowl	80.9	−0.8	−32.8	−9.6	106.2	28.3	21.1
+biolSces+sharedKnowl	87.1	3.3	−27.0	−3.0	123.6	31.1	25.1
+FMSY	8.7	14.5	13.7	9.1	25.3	4.5	6.7
+FMSY+biolSces	−1.4	−6.5	1.1	3.9	3.8	1.2	1.2

vessels could have opted to leave Baltic areas to travel to the North Sea as exhibited by changes in landing compositions for Kattegat and North Sea stocks (Figure 4).

Effects on individual vessels

At the individual vessel level (Figure 8) and within all harbour communities (Supplementary Materials S5), most of the simulated vessels experienced losses according to GVA and VPUF indicators for the tested biological scenarios (more than half of the vessels in the cumulative scenario +biolSces). The fishery scenarios in combination with the lower biological production regime led to more extensive effects at the individual vessel scale compared with those experienced at the fleet scale where some vessels lost significantly on both indicators when they attempted to save fuel (+biolSces + saveFuel), to respond to fish prices (+biolSces + priceTargets), or to select fishing grounds according what other vessels did (+biolSces + sharedKnowl). However, for most of the individual vessel fishery scenarios, it was found to be more common to increase profits to the detriment of energy efficiency levels. Finally, we also found that some vessels can actually benefit from the scenarios in terms of both indicators, and this was mainly found to be the case for 20% of the vessels that could save fuel.

BCOD F_{MSY} approach

When the LTMP is abandoned and the F_{MSY} approach is applied exclusively (as defined in 2012) for both cod stocks, outcomes change toward more sustainable exploitation as indicated by F (Figure 5) and SSB levels (Figure 3), while revenues from catches increase for both stocks (Figure 3) based on higher advised TACs. These TACs are furthermore not constrained from year to year. However, the F_{MSY} approach does not accommodate changes in stock conditions and stock mixing, and landings are reduced (Figure 4) in the long term while Eastern cod levels are on a collapse trajectory unless F_{MSY} values are frequently updated to adapt to changes in productivity and migration rates (Figure 3). The F_{MSY} approach has minor effects on fishing effort distributions over Baltic areas relative to the baseline condition (Figure 7 and Table 3).

Discussion

By integrating biological and fishery dynamics and interactions between the MSE and scenario analyses we obtain a stronger understanding of interlinked dynamics and key influencing factors and of consequences for exploited populations and the fishery economy when introducing different management and stock production options (Prellezo *et al.*, 2012; Voss *et al.*, 2014; Nielsen *et al.*, 2015). This is of direct relevance to the identification of levels of exploitation that could safeguard the viability of fisheries and coastal communities that are dependent on these resources (Prellezo and Curtin, 2015). These aspects are also of crucial importance to BCOD fishery management schemes where recent changes in stock production and migration have challenged stock assessment and management systems. This has compromised trusted knowledge on the biological traits of cod stocks and on associated fisheries even though western cod assessments are currently considered reliable. Fixed F targets can be used to generate long-term management stability, as targets are not designed to change or be updated frequently. This aspect *de facto* assumes constant recruitment, growth, fishing patterns, maturity, and natural mortality even when uncertainty ranges around values are high (Cadigan, 2013). A significant change in any underlying biological feature in a certain direction that heavily influences F_{MSY}-levels would likely bias and invalidate the relevance of the targets. The results of the present model simulations show that profitability levels are largely reduced by declining cod stocks irrespective of LTMP settings, and targets are unable to perceive changes in stock productivity and spatial dynamics (e.g. extensive migration and stock mixing).

Based on the simulations performed under various stock conditions, lower growth and stock mixing between east and west cod stocks seems to result in high risks of Eastern cod stock collapse. It comes as no surprise that such collapsing trajectories are by far the most influential factors affecting economic fishery outcomes. Danish fisheries accordingly incur large economic losses due to low productivity levels, and neither the tested alternative spatial re-allocation of effort plan nor the harvest control rule specified through the EU long-term BCOD management plan can alleviate this. Consequences of factors that could negatively affect

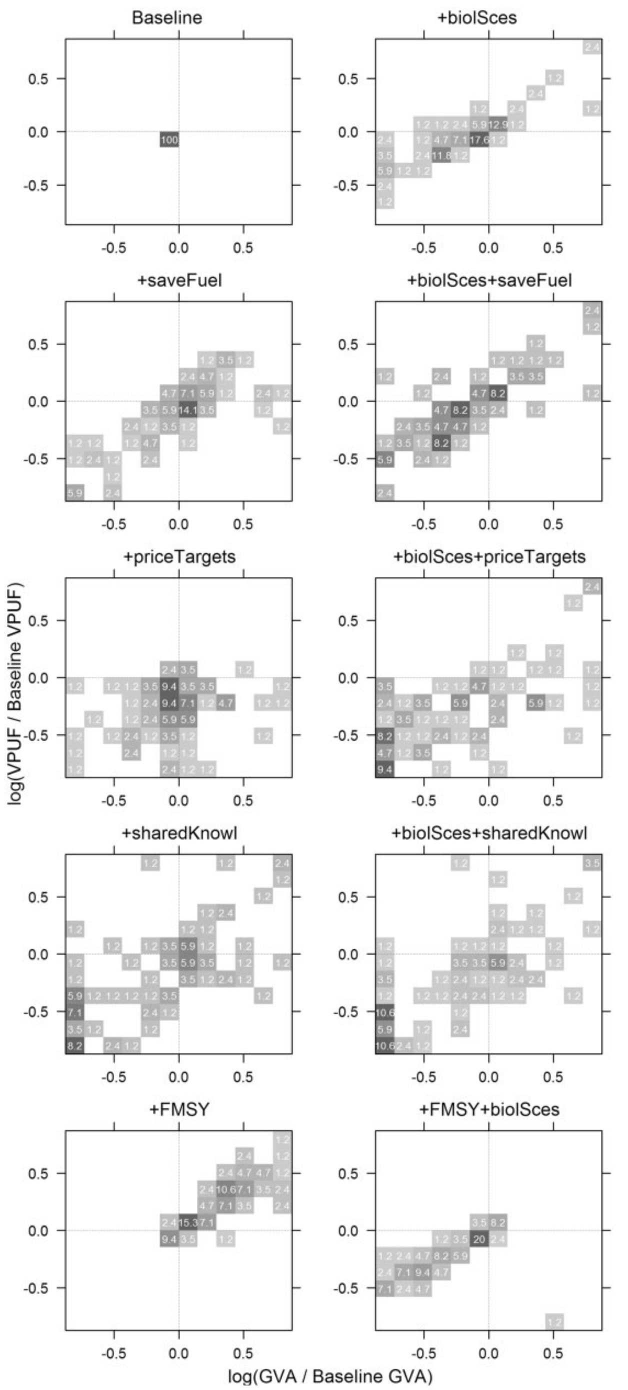

Figure 8. GVA vs. VPUF values for each scenario relative to the baseline condition. Fishing vessels gaining on both GVA and VPUF indicators relative to the baseline are shown in the upper right-hand area. Ratios are log-transformed to make the visualization clearer. Each grid cell colour represents the percentage of vessels (from the BCOD fisheries) sharing axis values, and the percentage of vessels in each cell is also given. Monthly vessel-specific VPUF values are averaged for the entire simulated period. The vessel-specific GVA values of each trip are summed for the entire simulation period. Both indicators are also averaged over 50 stochastic runs per scenario.

cod growth [e.g. ecological factors such as hydrographic conditions, the parasitic infestation of cod transmitted from seals, or food depletion (Eero *et al.*, 2015)] should be considered when ensuring cod stock sustainability.

Our findings indicate that stock mixing between eastern and western cod may have affected each stock differently. Eastern cod stock is highly impacted when part of the population (mature adult fish) migrates west even when some of the fishing pressure is displaced to the western Baltic. Consequently, the fishing mortality of eastern cod increases mechanically beyond sustainable levels given that the eastern cod quota is east area-based and is additionally composed of smaller fish. Fishing pressures on western cod stocks have also increased due to east-west effort reallocation patterns. If migrants from east to west (*SD*24) lead management procedures based on higher TAC advice from a biased view of true stock conditions, this would increase the *F* level for western cod, and catches may also consist of Eastern cod.

The effects of stock mixing from the simulation outcomes are conditional on available knowledge on annual cod migration rates and on whether return migration is taking place or not. These processes are still not fully understood, and the current ICES analytical stock assessment does not operate based on such fluxes, as it rather allocates annual proportions of catches taken in *SD* 24 to eastern and western population components (ICES, 2015). The two stocks have distinct spawning periods and are genetically distinct, suggesting that they do not interbreed and only overlap in their distribution areas. Eastern BCOD also regularly use *SD* 24 for spawning (Bleil *et al.*, 2009; Hüssy 2011), and thus it is unclear whether return migrations due to natal homing occur. Furthermore, at this stage, quantitative knowledge on *SD* 24 spawning ground contributions to the recruitment of different cod sub-populations (relative to the role of the *SD* 22 or 25) is limited (Hüssy *et al.*, 2016). Since 2015, BCOD has been assessed according to biological stock components rather than by area (management area), i.e. taking into account migration and stock mixing in assessments (ICES, 2015). Our results demonstrate that integrating such complexities into recent stock assessments is critical in mitigating the negative impacts we document here in relation to management systems for both stocks. The most recent stock assessment indeed revealed a different stock trajectory of western cod populations than was previously anticipated based on area-based assessments that included cod from eastern populations found in *SD* 24.

Our findings suggest that the F_{MSY} approach would be more suited to sustainable exploitation and would generate higher revenues for both BCOD stocks (if the stock biology remains the same). At the time of writing this report, the LTMP is still formally in force, and thus we base our simulations on rules defined by the LTMP. However, management advice on western BCOD currently follows the MSY approach and is based on an ICES data-limited approach designed for eastern cod. Unfortunately, the fixed F_{MSY} approach was found to be insufficient and not robust enough in our simulations to ensure stock sustainability in the long term when an underlying change in stock conditions and potential migration across management areas occurred. However, two specific aspects of the F_{MSY} approach are likely to improve management systems in accordance with changes in stock biological conditions by (i) introducing a B_{MSY} trigger given the $B_{trigger,\ MSY,}$ which may act to safeguard stocks beyond the tested horizon and by (ii) removing constraints on the TAC to increase levels of flexibility in adapting to unexpected changes. In reality, management systems may be adjusted so that the TAC constraint is paused when stocks are at risk, and if this is not tested, our findings suggest that it is unavoidable when the biological regime can change as it can for interlinked BCOD stocks.

In retrospect, the overall and local economies were likely affected differently by negative consequences of declining stock trajectories. BCOD mis-management could have resulted in some unintended unequal consequences on the stakeholders, fleets and fishing communities. At the individual scale, the results of all of the scenarios tested show that there may be more losers than winners among vessels, and this may create social concerns. Typically, larger vessels participating in fisheries are more polyvalent than small vessels with respect to covered stocks and areas, and this effect appears to be worse for smaller vessels, which are less mobile and capable of re-allocating their efforts to other stocks and areas. That is, they are more dependent on cod catches from home waters. Identifying who will be the most affected is, however, largely dependent on individual (skipper) reactions and motives and on vessel ranges to some extent. Our simulations indeed show that fishery displacement toward less frequently visited or new fishing grounds could have as much of an impact on the economics of individual vessels as biological scenarios alone without replacing efforts, confirming that some of the greatest effects on fishing power arise from individual choices (Mahevas *et al.*, 2011). Methods for predicting effort allocation schemes outside of the vessel "comfort zone" and for implementing opportunistic behaviours at the vessel scale remain complex. For example, the present scenario wherein vessels share knowledge on their preferred fishing grounds shows that most of these new grounds have been suboptimal for most vessels (some of them even decided to leave the Baltic Sea). This led to an abrupt decrease in individual and overall profitability. Hence, obvious non-linear effects of the displacement of fishing efforts on stocks further encourage the use of modelling tools to anticipate them (Glaser *et al.*, 2014). We consider the use of decision trees for individual vessel decision-making as a necessary path forward in exploring such factors and their consequences.

An additional challenge related to individual vessel and fleet-based simulations pertains to the fact that they require a large amount and range of data to be managed in a unified way within a common framework (e.g. Bastardie *et al.*, 2014; Gourguet *et al.*, 2014; Mangel *et al.*, 2015). This creates opportunities to incorporate potential errors from input data or approximations that may further affect outcomes. For example, the distribution of spatial fishing efforts and catches is obtained from logbooks and via VMS coupling (see Hintzen *et al.*, 2012) with some assumptions being relative to analyses of VMS tracks (the fishing event detection method in particular), and spatial and vessel CPUE computing is dependent on this information; time and space processes are discretized and dynamics occur at various scales (hour, month, quarter, semester, and year) and over a grid of cells of fixed size (4×4 km); vessels are assumed to have their own catchability level, and this catchability level varies with the stock abundance value and with no effects of technological improvements in the long run. Another key issue pertains to describing the spatial distribution of stocks and their spatial dynamics. Meanwhile, a shrinkage of the spatial distribution can occur at various levels of abundance, leading to misleading cases of catch rate hyperstability (Harley *et al.*, 2001). Given the importance of maintaining the spatial structure of exploited fish stocks (Watson *et al.*, 2011; Ciannelli *et al.*, 2013; Nielsen *et al.*, 2014) the model should refine the spatio-temporal dynamics of populations to account for explicit movements and connectivity levels between areas. We foresee that better estimating the underlying relative resource density and availability levels of fisheries will allow for more precise descriptions of fisheries and individual vessel-based specific fishing power levels, fish catchability levels, and partial fishing mortality levels (see e.g. Nielsen *et al.*, 2014 for a detailed modelling of resource abundance surfaces and densities based on research surveys using a stochastic correlation model for western BCOD and whiting). However, whether these effects expand uncertainty intervals without changing impact directions should also be clarified.

In conclusion, this study addresses the important issue of mismatch between management and biological units and the potential consequences of not incorporating this bio-complexity in assessment and management. This study shows that the recent deterioration of eastern cod stock has been aggravated by a decoupling of the advised harvesting level for years targeting an inappropriate *F*-level and what the stock was capable of supporting under a productivity decline (decline in the abundance of large fish) as shown by collapse trajectories arising from our simulations of declining growth and increasing mortality. Other authors have also stressed that overconfidence in model forecasts and projections, and in fish stock assessment models including errors in their input data in particular, may have dramatic implications for fishery management schemes (Longhurst, 2010; Brander *et al.*, 2013; Dickey-Collas *et al.*, 2014; Brooks *et al.*, 2015; Planque, 2015), and recent *ad hoc* ICES stock assessment and forecasting efforts have attempted to account for changes in productivity on an annual catch forecast basis. In this study, we quantified profitability losses that result when vessels only rely on poor status cod stocks. Simulated changes are induced depending on how individual vessels select their fishing grounds with consequences on fishing costs, energy efficiency and profitability. For most of the vessels and fishing communities investigated, the model found no other way to compensate for losses than to redirect some fishing efforts to western areas, placing additional pressures on western cod stocks. It is important that fisheries managers become aware of such unbalanced social and economic consequences when making mis-management. The novelty using the present type of model for such evaluations is that this model exactly enables us to inform about such skewed effects. In modelling fisheries, the prediction of radical changes remains uncertain with fishermen's decision-making falling outside of historical space. Fishermen could have responded to fluctuations in resource levels, to various management actions, and to space constraints while still electing to remain within the boundaries of known space. Due to sensitivities to alternatives in individual decision processes involved in fishery operation, our findings also support the notion that describing and modelling individual decision-making factors and their dynamics in detail bolsters the predictive power of fishery system modelling and evaluation. This is especially true when considering socio-economic causes and consequences. Accordingly, involving stakeholders in such scenario evaluations is essential when evaluating the extent to which decisions are realistic and such an approach should be facilitated through the existing modelling platform.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the article.

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Appendix A - Discrete catch process and removals within DISPLACE

Removals R from the fisheries are deduced from a catch equation linking vessel specific catch rates to stock abundances per area (graph nodes). Parameters are obtained by applying a negative binomial generalized linear model per stock on the observed landing in mass per unit effort, aggregated per vessel, fleet-segment (métier) and area:

$$\begin{aligned} Log(\mathrm{E}(LPUE_{\mathrm{stock,vessel,metier,area}})) &= \beta_{\mathrm{stock,vessel}} + \gamma_{\mathrm{stock,metier}} + \sum_{\mathrm{size} \epsilon \mathrm{szgroups}} \delta_{\mathrm{stock,size}} \\ &\quad \times SEL_{\mathrm{stock,size,metier}} \times \mathrm{AV}_{\mathrm{stock,size,area}} \end{aligned} \quad (1)$$

where E(LPUE) denotes the expected *LPUE* for stock in the area with model class variables (β, γ, and δ) including vessel and métier effects, the length-based stock availability AV of a size group specific to this area, and the métier/gear selectivity SEL value (selection ogives depend on selectivity specific parameters L50 and L75 relative to the gear type deployed by different métiers). The availability, i.e. the share of the population across areas, is deduced from scientific vessel surveys (BITS and IBTS).

The landings L in kilos performed on a given stock during a t period are obtained by multiplying the vessel and stock specific (LPUE) catch rates (kg per hour) with the deployed fishing effort (usually 1 h).

Due to the discrete event modelling procedure, the order of fishing effort application to stocks is crucial, and the active vessel order is shuffled randomly throughout the same simulation or across simulation replicates.

Landing numbers per size group L_{size} are deduced based on underlying available biomasses per area (i.e. biomasses on each node) and based on size distributions over these areas:

$$\begin{aligned} L_{\mathrm{size}}(\mathrm{t}) &= (N_{\mathrm{size}} \times Sel_{\mathrm{size}} \\ &\quad \times W_{\mathrm{size}}) / \left(\sum_{\mathrm{size}>\mathrm{MLS}} N_{\mathrm{size}} \times Sel_{\mathrm{size}} \times W_{\mathrm{size}} \right) \times L(\mathrm{t}) \end{aligned} \quad (2)$$

Depending on the biomass per size group available to a fishing event, W is the weight of the size group with the total landed L in kilos. Hence, the amount landed here is the portion of the catch retained by fishing gear and composed of animals with a body size greater than the enforced minimum landing size (MLS). The portion with animals smaller than the MLS is the discard D and is deduced from the total landing L, the scaled N of size, the selectivity curve Sel and the MLS as follows, if I exceeds:

$$\begin{aligned} D(\mathrm{t}) = &\left[\int_{-\infty}^{\mathrm{size}=I} Sel_{\mathrm{metier}}(x)\mathrm{d}x \; + \; \int_{I}^{\mathrm{size=MLS}} N_{\mathrm{size}}(x)\mathrm{d}x \right] \Big/ \\ &\int_{\mathrm{size=MLS}}^{+\infty} N_{\mathrm{size}}(x) \; \mathrm{d}x \; \times L(\mathrm{t}) \end{aligned} \quad (3)$$

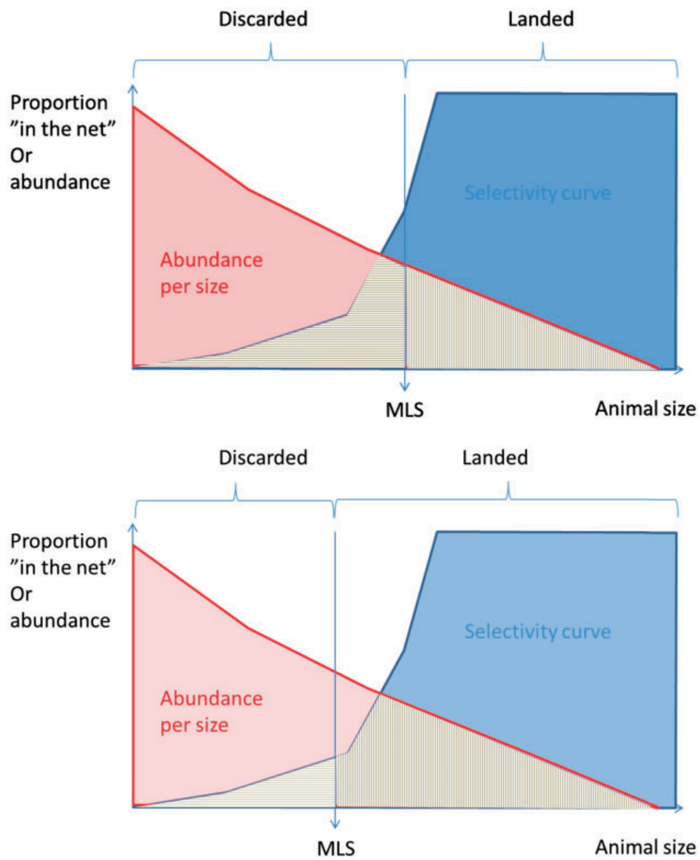

Figure A.1. Theoretical surface area, discard and landing fractions of the total catch while computing definite integrals depending on the MLS relative position on distributions of the stock abundance (red curve) and on the size-specific selectivity of the gear type in use (blue curve). Top: when the selectivity curve exceeds the sized-based abundance curve at MLS. Bottom: when the selectivity curve falls below the MLS.

if I is less than:

$$D(\mathrm{t}) = \int_{-\infty}^{\mathrm{size=MLS}} Sel_{\mathrm{metier}}(x)\mathrm{d}x \Big/ \left[\int_{\mathrm{size=MLS}}^{I} Sel_{\mathrm{metier}}(x)\mathrm{d}x + \int_{\mathrm{size}=I}^{+\infty} N_{\mathrm{size}}(x)\mathrm{d}x\right] \times L(\mathrm{t}) \quad (4)$$

Given that the size I at the intersection of the selectivity curve and abundance per size curve is rarely precisely found at MLS, the integral calculation must adapt to this (see Figure A.1) depending on whether the selectivity curve exceeds the sized-based abundance curve at MLS or vice versa.

Discard numbers per size group D are then deduced based on the underlying available biomass with the total discarded value in kilos:

$$D_{\mathrm{size}}(\mathrm{t}) = (N_{\mathrm{size}} \times Sel_{\mathrm{size}} \times W_{\mathrm{size}}) / \left(\sum_{\mathrm{size<MLS}} N_{\mathrm{size}} \times Sel_{\mathrm{size}} \times W_{\mathrm{size}}\right) \times D(\mathrm{t}) \quad (5)$$

The discard rate is computed as the amount discarded over the amount discarded added to the amount landed.

The total removals R is the sum of landings (per size group) and discards (per size group) that, at each time step, is subtracted from the total N abundance (per size group) present in this area (node). When removals are greater than numbers available in the area, removals are equal to the available numbers, meaning that the N is set at zero in this node, and landings and discards are corrected for this fishing event.

In cases of total allowed catches management or individual quotas, stock-specific quotas are decreased by the amount that will be landed upon returning to a port. Meanwhile, any overshoot of the (overall or individual) quota is added to the discards. Each vessel continues to fish as long as it has some quotas left on Baltic cod stocks, otherwise it remains stationed quayside.

At the end of each trip, revenues are computed at a port from landed times of the port-specific price per marketable category, and the gross value added is computed from the actual operating costs of the trip. At the overall scale and at the start of each month, an overall fishing mortality F is deduced:

$$F_{\mathrm{stock}}(\mathrm{t}) = -\log\left(\sum_{\mathrm{size}} N_{\mathrm{size}}(\mathrm{t}) / \sum_{\mathrm{size}} N_{\mathrm{size}}(\mathrm{t}-1)\right) \quad (6)$$